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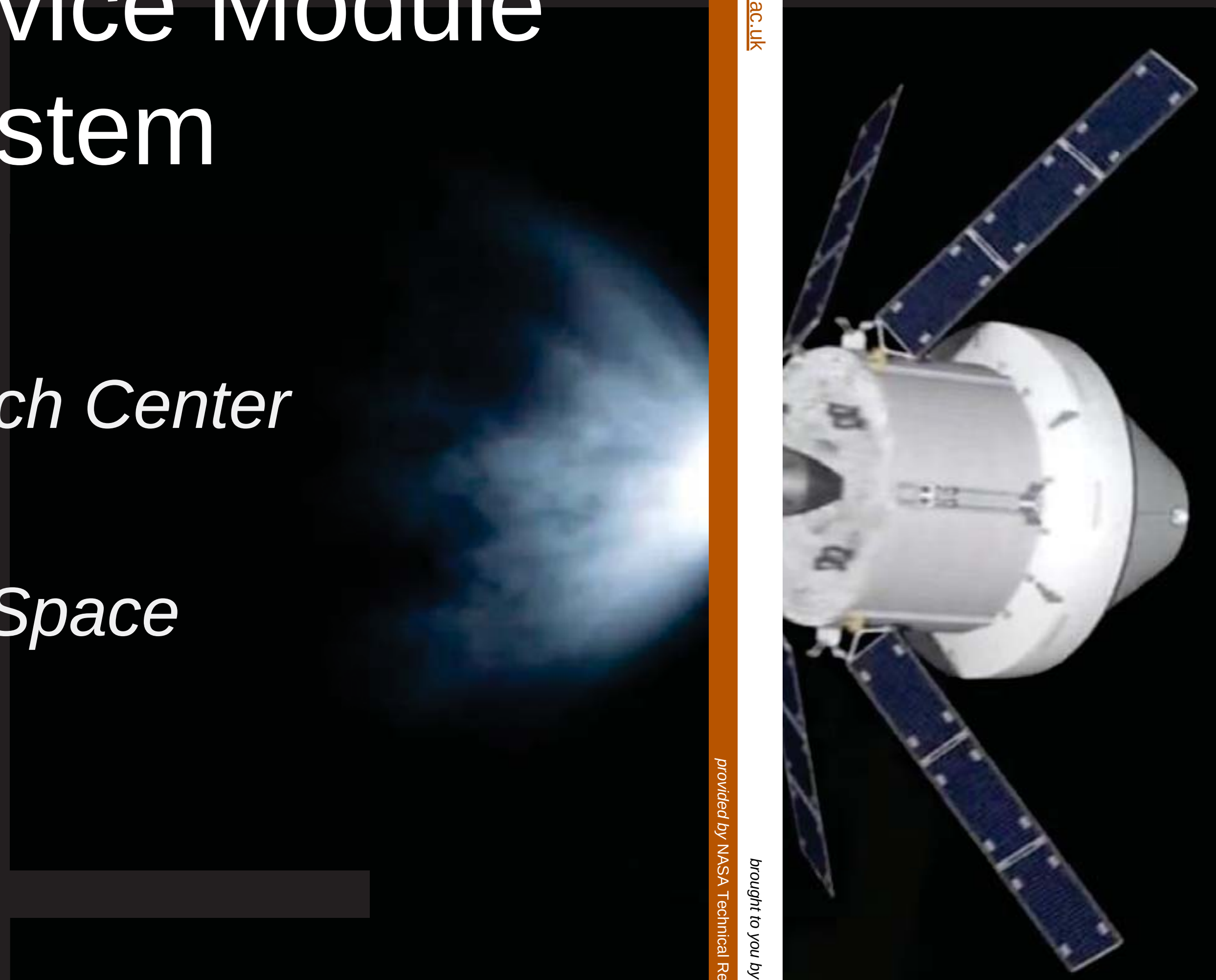
Plume Impingement Analysis for the European Service Module Propulsion System



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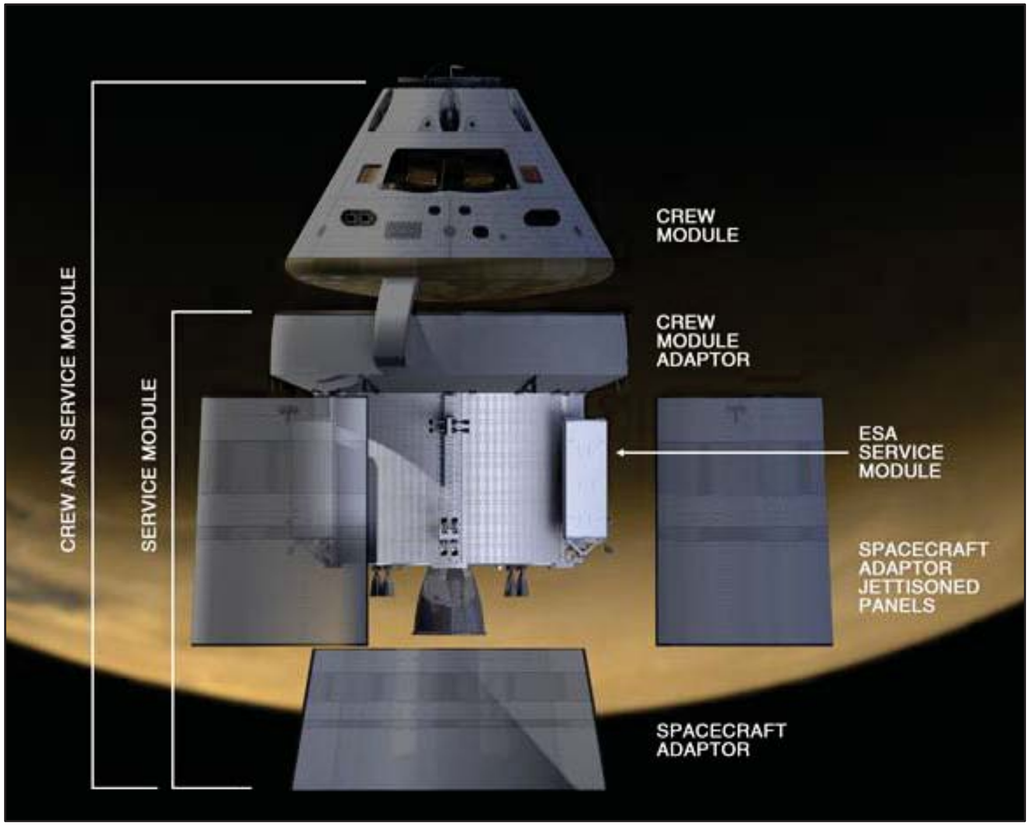
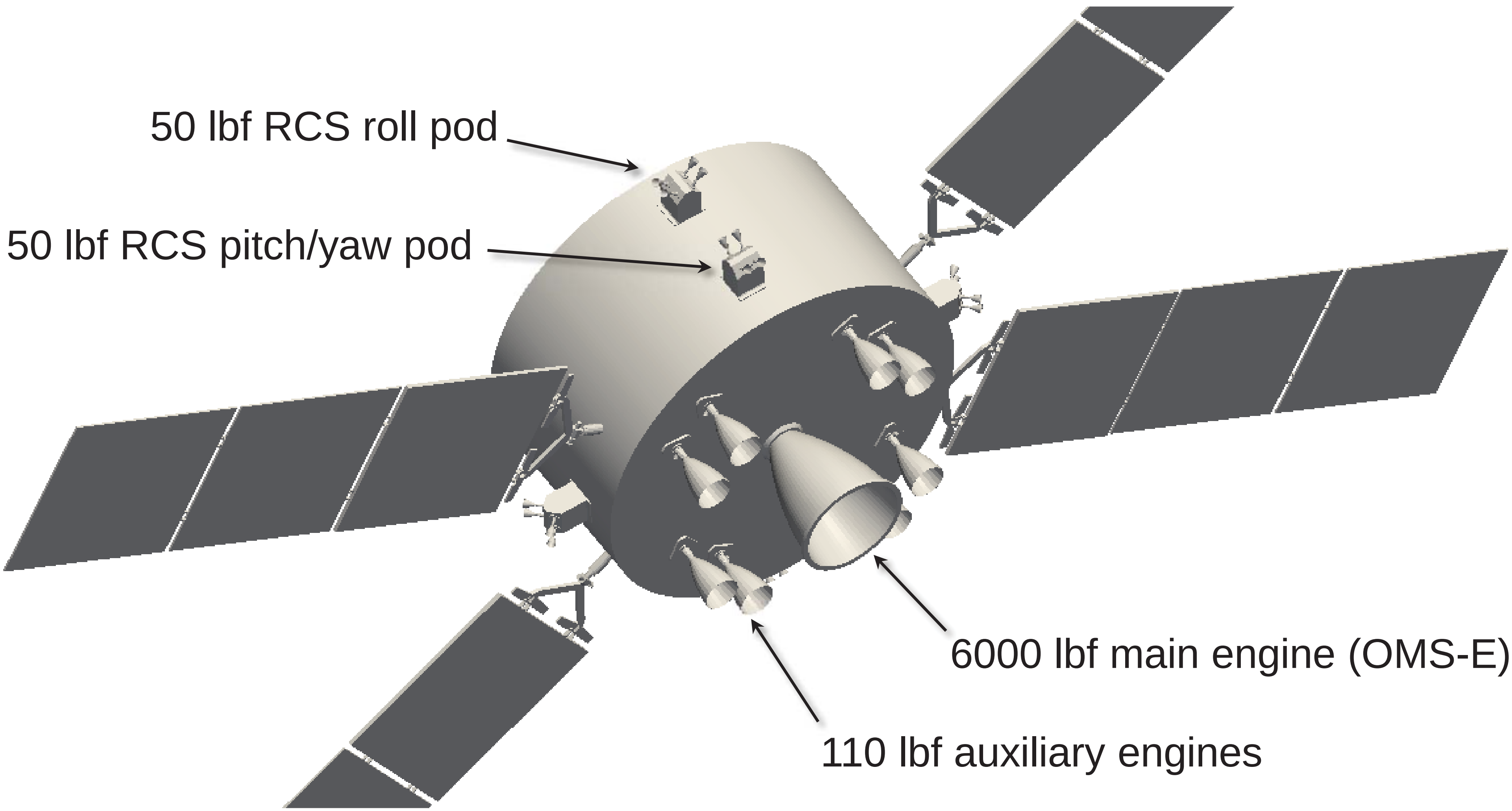
ESM overview

- The European Service Module (ESM) is part of the Orion spacecraft
  - Houses primary power, thermal, and propulsion systems for Orion
  - ESM development derived from Automated Transfer Vehicle (ATV) design



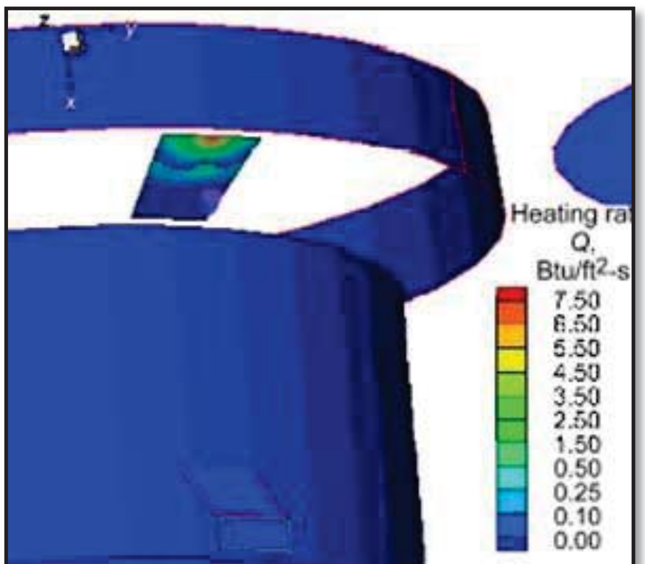
ESM prop sys overview

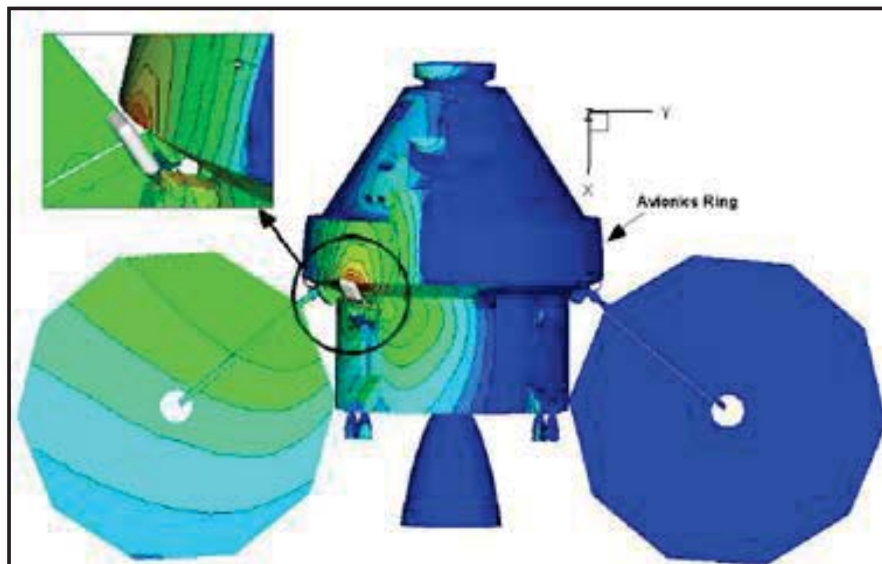
- The ESM has three main engine classes



Prior plume analysis

- Plume impingement is an area of spacecraft design that requires significant analysis
  - Thermal loads, contamination, erosion, and induced moments are some of the areas of concern with plumes
  - Prior work was performed on the previous iteration of the SM design





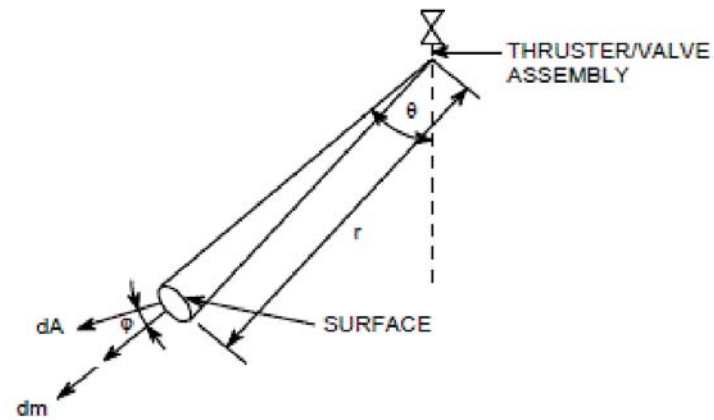
SM design changes

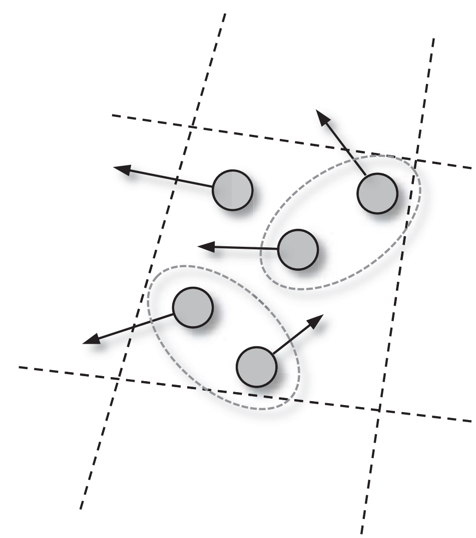
- There a few significant changes from the prior program of record versus the current ESM effort:

Before	Now
150:1, 1.85 MR, 7500 lbf main engine	55:1, 1.65 MR, 6000 lbf main engine
164:1, 1.85 MR auxiliary engines	300:1, 1.65 MR auxiliary engines
16 qty, 100:1, 25 lbf RCS engines	24 qty, 50:1, 50 lbf RCS engines
2 circular solar arrays	4 rectangular solar arrays

Plume models

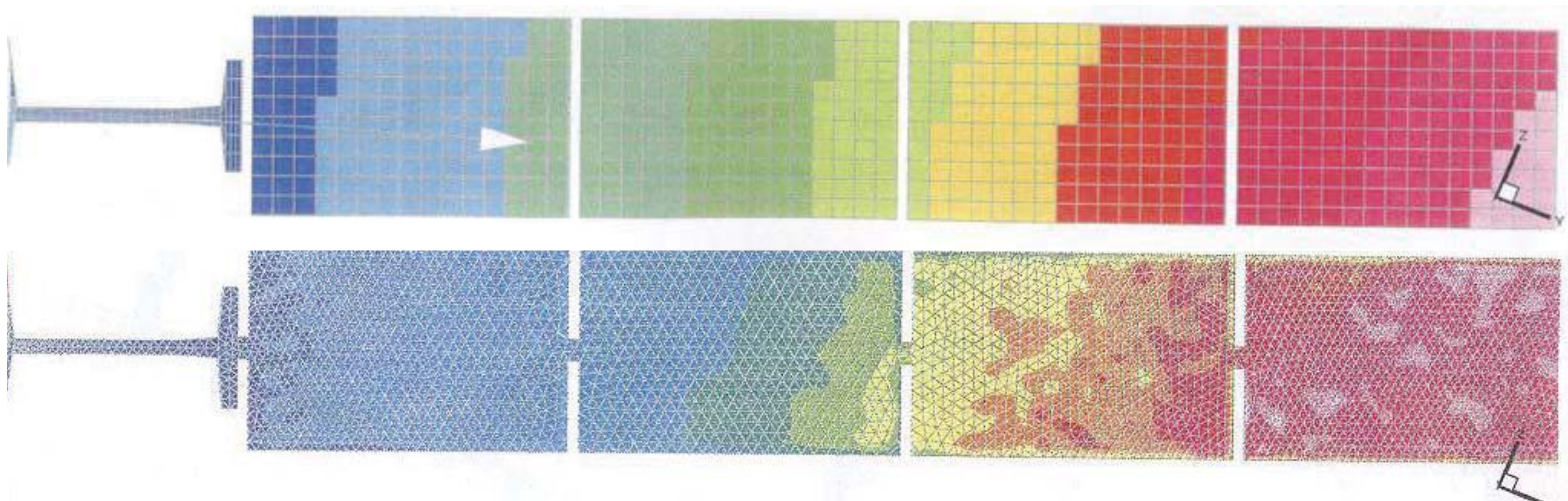
- Plume impingement modeling was performed by both Airbus and NASA
  - Airbus employed two models:
    - » RAYJET
    - » Internal External Monte Carlo (IEMC)
  - NASA used two models:
    - » Reacting And Multi-Phase (RAMP2) / PLume IMPingment (PLIMP)
    - » Hypersonic Aerothermodynamics Particle (HAP)





Airbus plume models

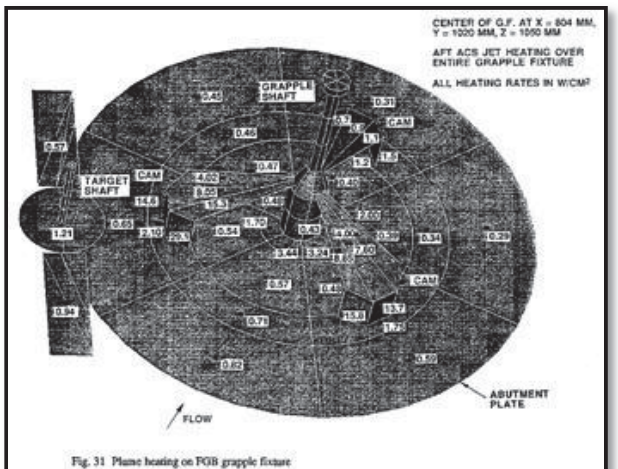
- Airbus used two models to analyze the plume
  - RAYJET uses a ray tracing method with properties simulated by a fitting function deduced from Monte Carlo simulations
  - IEMC uses the DSMC method to simulate plume
  - Both codes have been successfully used for ATV



RAYJET (top) and IEMC (bottom) simulations for ATV plumes on solar arrays

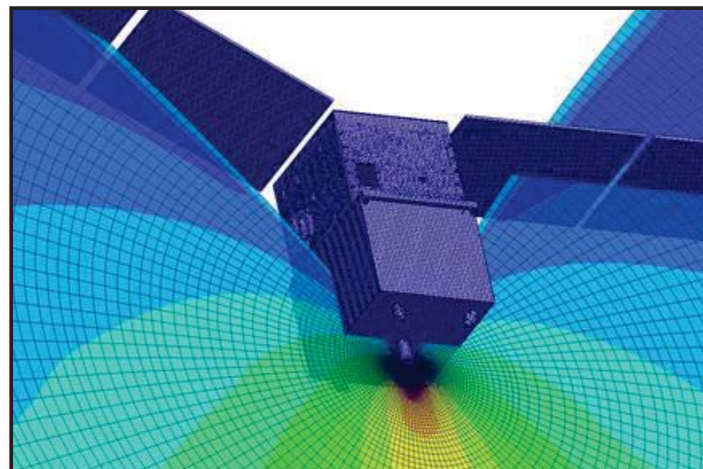
RAMP2 / PLIMP background

- RAMP2 / PLIMP has been successfully used on NASA programs for plume impingement calculations
  - RAMP2 based on method of characteristics to calculate plume flowfields
    - » CEA-equivalent code used to apply boundary conditions at thruster throat
  - PLIMP applies RAMP2 results to calculate surface impingement properties



Shuttle PRCS plumes onto ISS

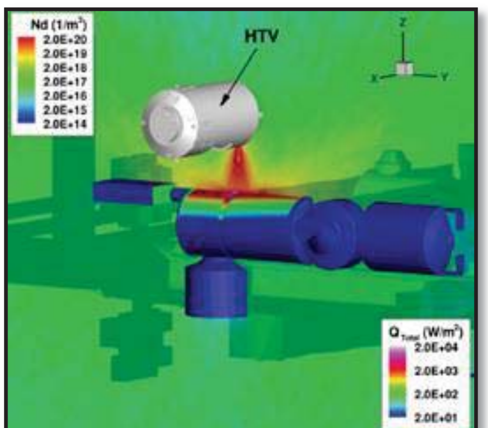
SLS SRB plume



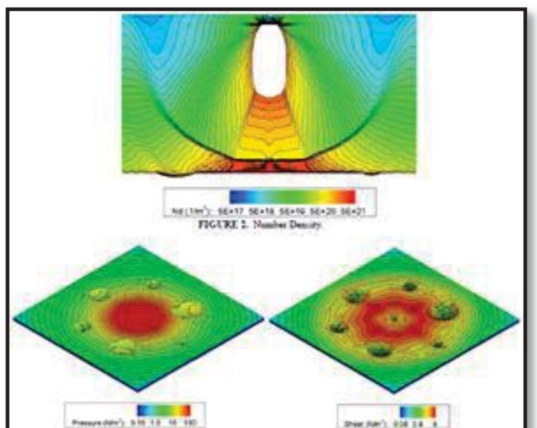
GPIM plume

HAP background

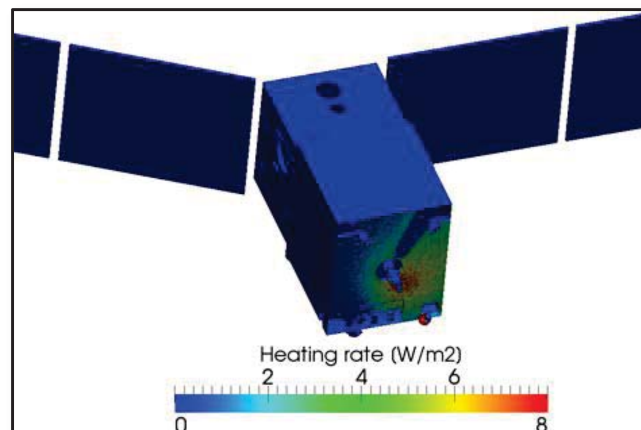
- HAP is based on the DSMC method
  - CEA results used for boundary conditions at exit plane
  - HAP has a implementation of a collision limiter to model low Kn flows without being overly diffusive
  - Other DSMC codes (e.g. IEMC, NASA DAC) have been successfully used for other plume studies



HTV plumes onto ISS



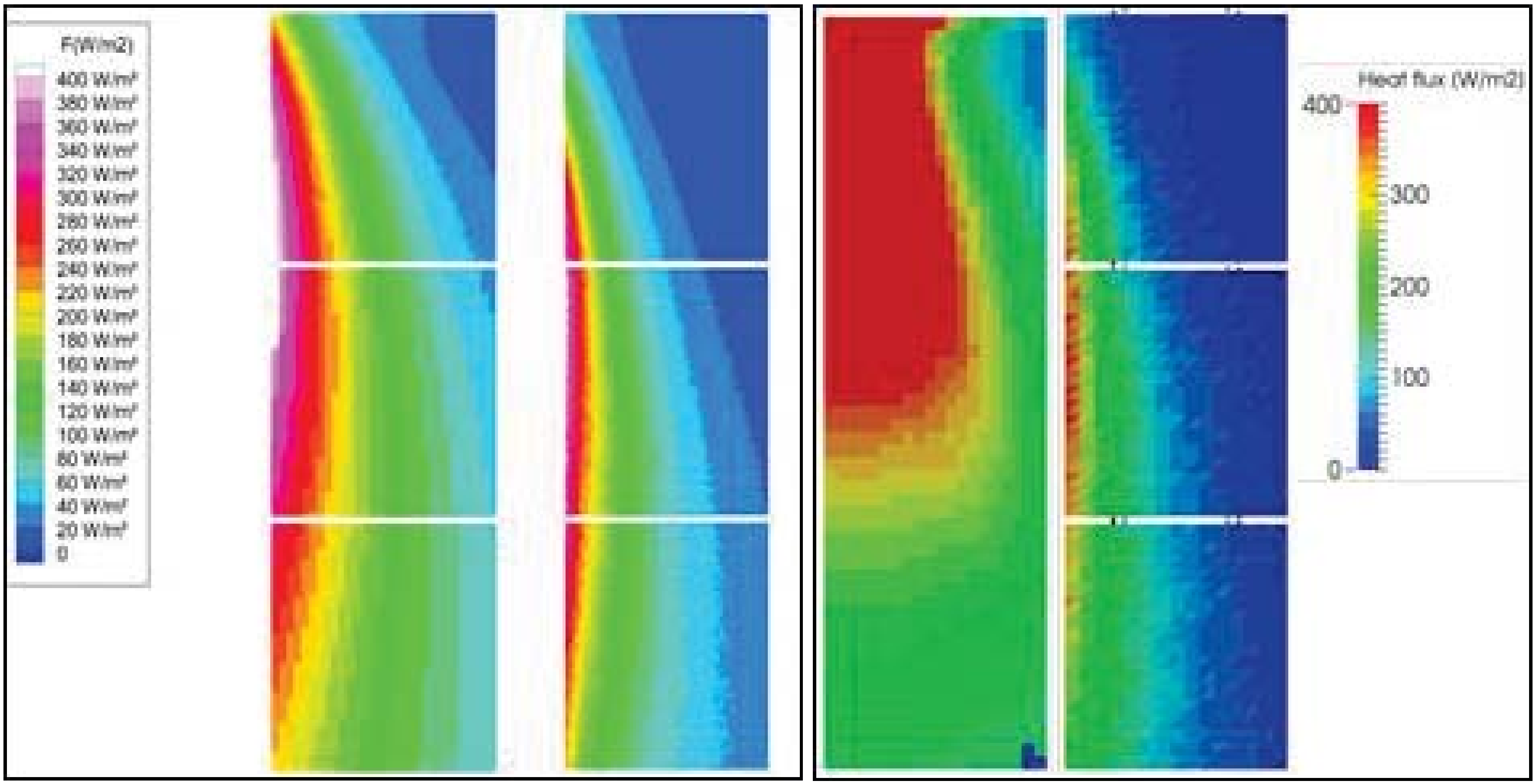
Altair lunar lander plume



GPIM plume

Model comparison overview

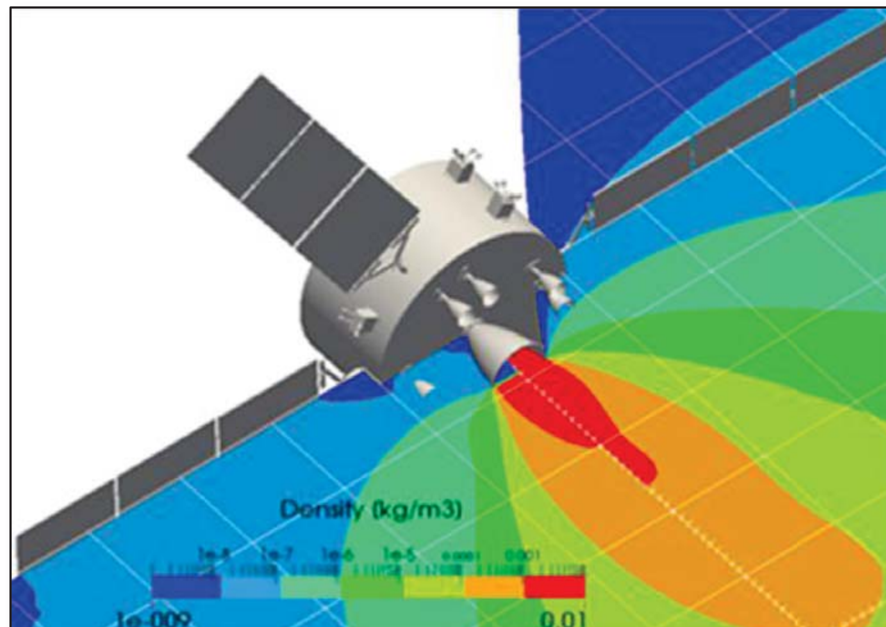
- A sample comparison among the different models



RAYJET IEMC RAMP2 PLIMP HAP

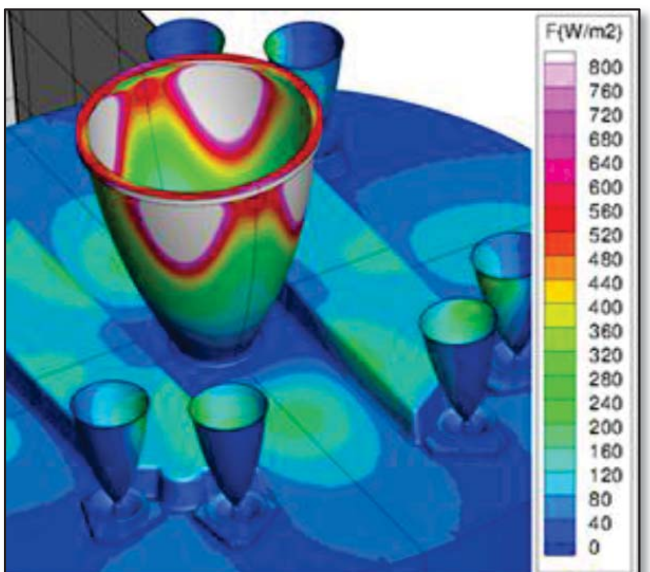
Main engine plume

- The ESM main engine plume is assessed for its impact on the solar arrays and aft end of the ESM
  - Max heating on both arrays and aft end is found to be < 0.1 kW/m^2
    - » Not a significant issue
    - » This is assessed with 0º solar array cant angle, arrays will likely be canted 55º away from engine for structural reasons

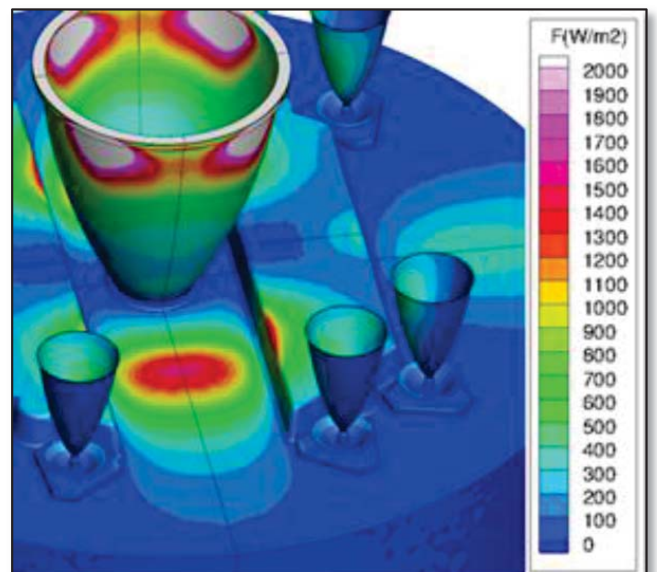


Auxiliary engine plumes

- When all 8 auxiliary engines are firing, the max heat flux on the aft end is 0.2 kW/m^2
- Including simultaneous OMS-E firing increases maximum heat flux to 1.6 kW/m^2
- Indicates notable plume interaction



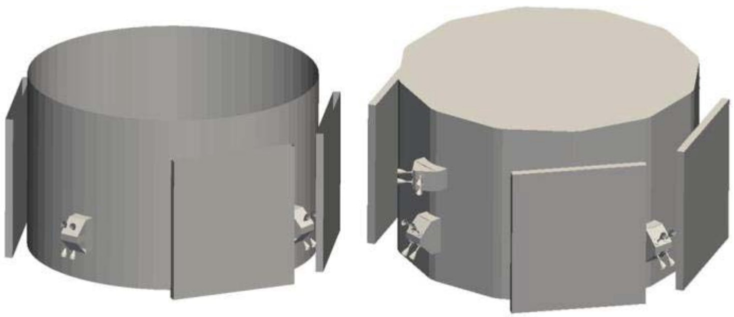
8 auxiliary engines

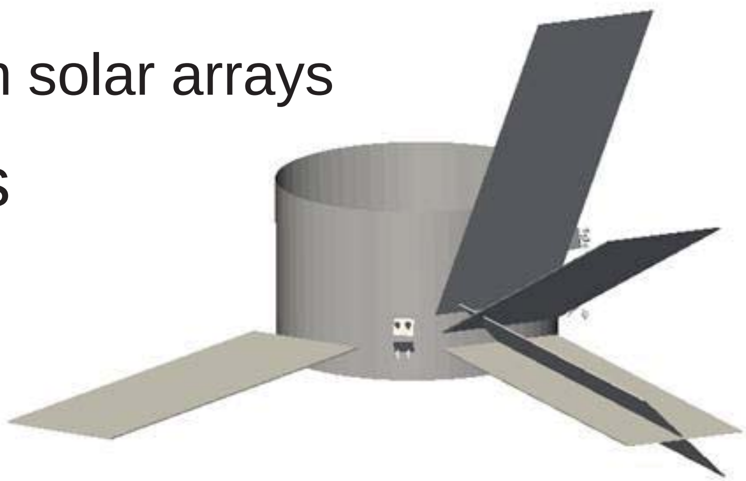


8 auxiliary + OMS-E

RCS engine plumes

- The RCS engine plumes need to be assessed for a number of different scenarios:
  - Different RCS engine configuration
    - 24 vs 16 RCS engines
  - Different RCS engines firing
    - Affects location and orientation of plume
  - Different pulse mode duty cycle and burn durations
    - Affects resulting allowable heat flux on solar arrays
  - Different solar array configurations
    - Cant and rotation angles



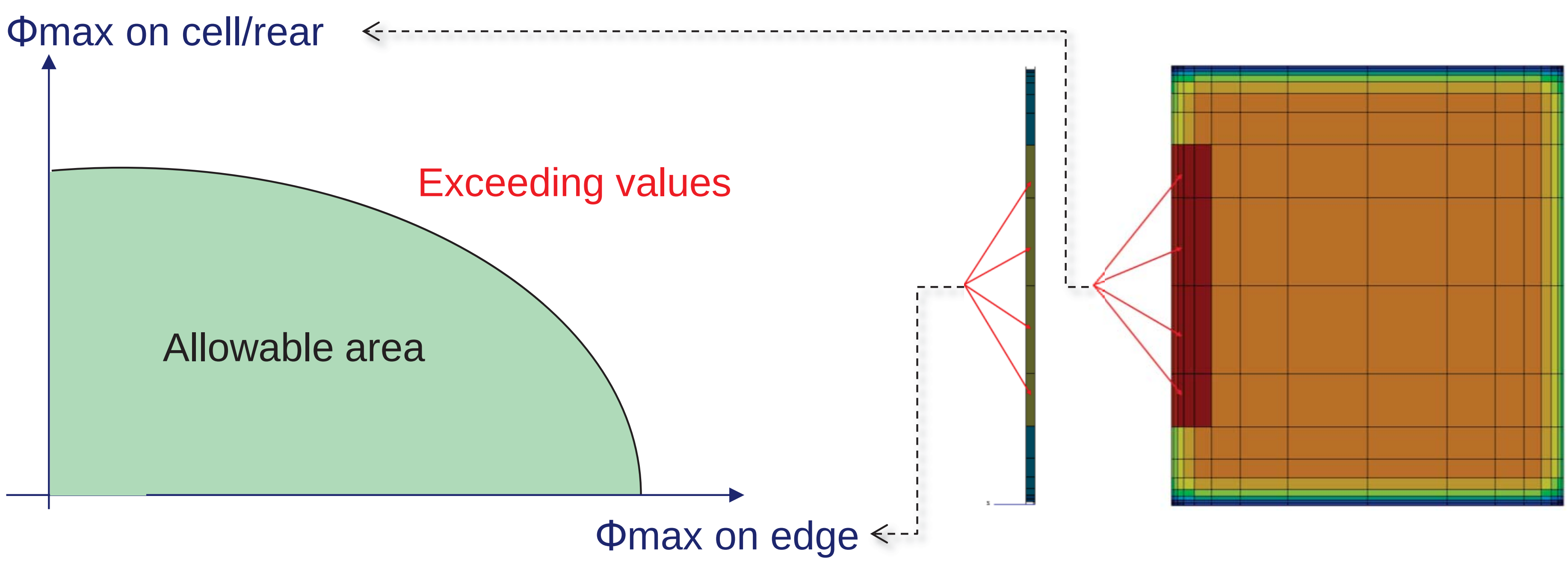


RCS engine plumes

- Four general scenario groups were found to be drivers for solar array heating
  1) Ascent abort scenario with stowed solar arrays
     » Stowed arrays are very close to RCS pods
  2) Free flight attitude control
     » Any solar array and firing RCS engine combination potentially possible
  3) Roll control during OMS-E or auxiliary engine burns
     » Roll plumes most directed towards arrays
  4) ΔV capability
     » Longest RCS burn durations

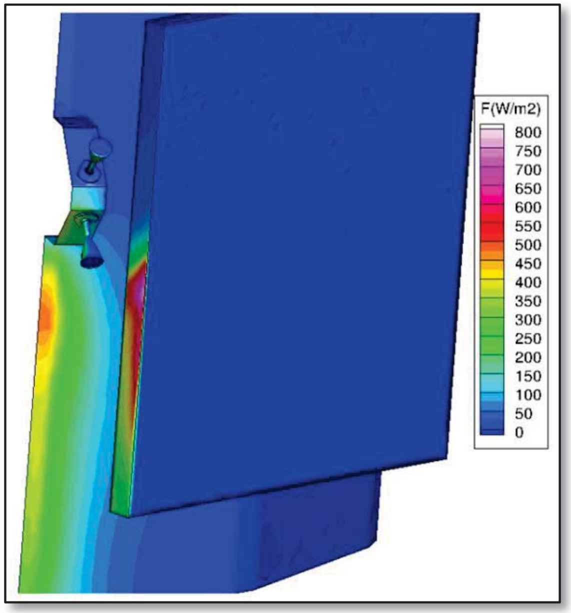
Solar array heating

- Allowable heat flux on solar arrays a function of
  - RCS engine burn duration and duty cycle
  - Heat fluxes on solar panel edge and solar panel face
  - Thermal analysis also accounts for other external thermal fluxes (e.g. solar, albedo)



RCS 1) abort

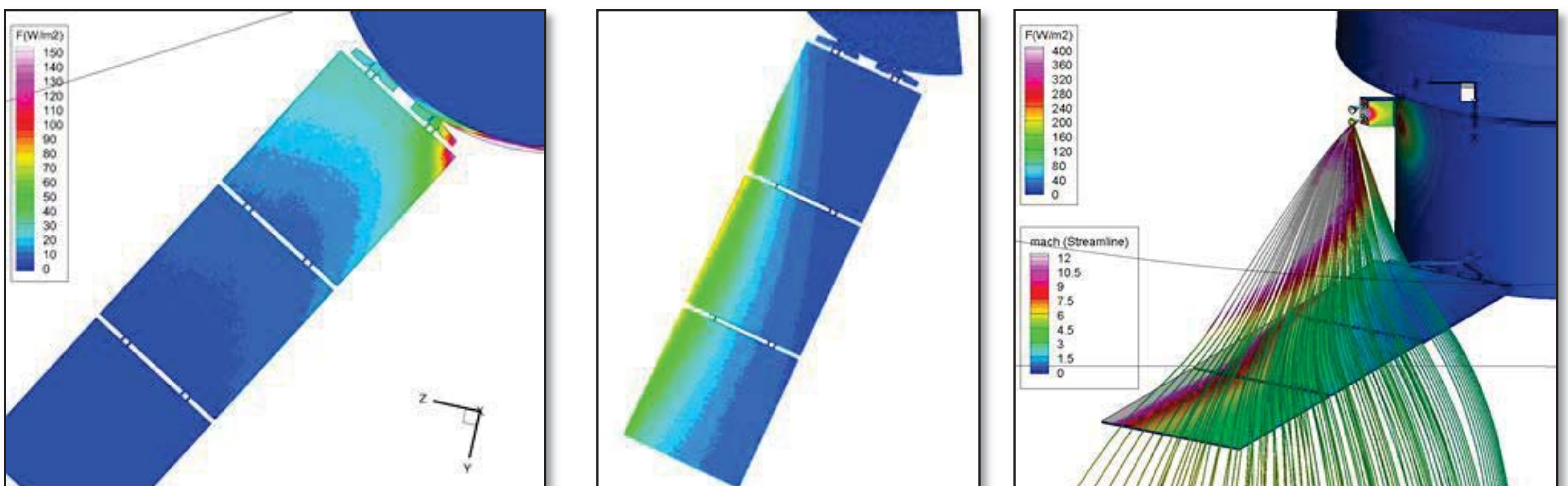
- For abort scenario
  - Solar arrays are stowed, located close to RCS pods
  - For 24 RCS engine config., max heat flux is 0.8 kW/m^2 on solar cell edge and 0.1 kW/m^2 on panel face
  - For 16 RCS engine config., max heat flux is 2.4 kW/m^2
  - However, max burn durations and duty cycles are relatively low
    - » Corresponding acceptable max heat fluxes on either array edge or face are > 10 kW/m^2



RCS plumes during abort scenarios acceptable

RCS 2) free flight ACS

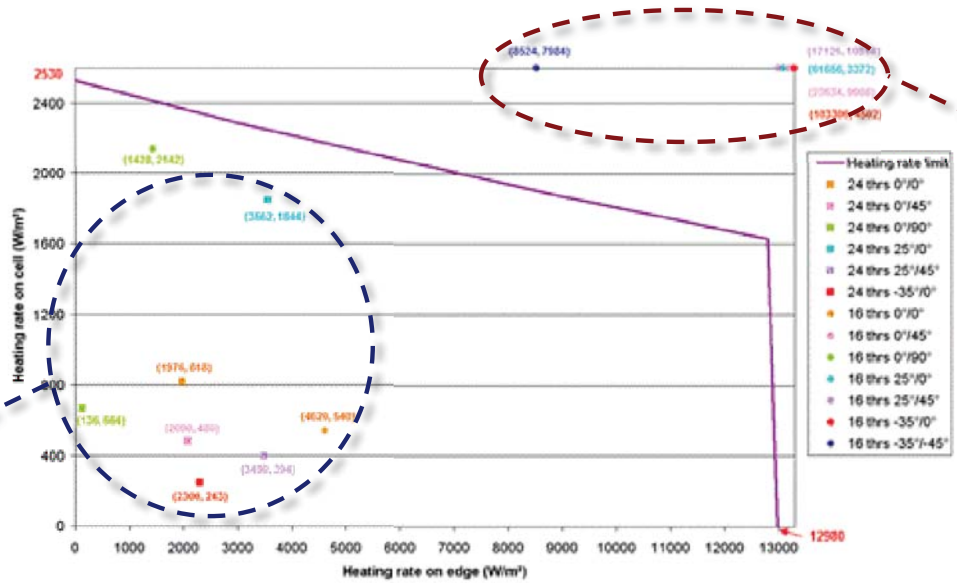
- For free flight attitude control
  - Solar arrays can be in any orientation
  - Any combination of RCS thrusters can fire
  - However, the expected RCS duty cycle is very low
    - » Allowable heat fluxes > 100 kW/m^2



RCS plumes during free flight scenarios acceptable

RCS 3) roll control

- For roll control during OMS-E or auxiliary burns
  - Solar arrays can be canted up towards RCS thrusters
  - Higher RCS duty cycles limit allowable heat fluxes



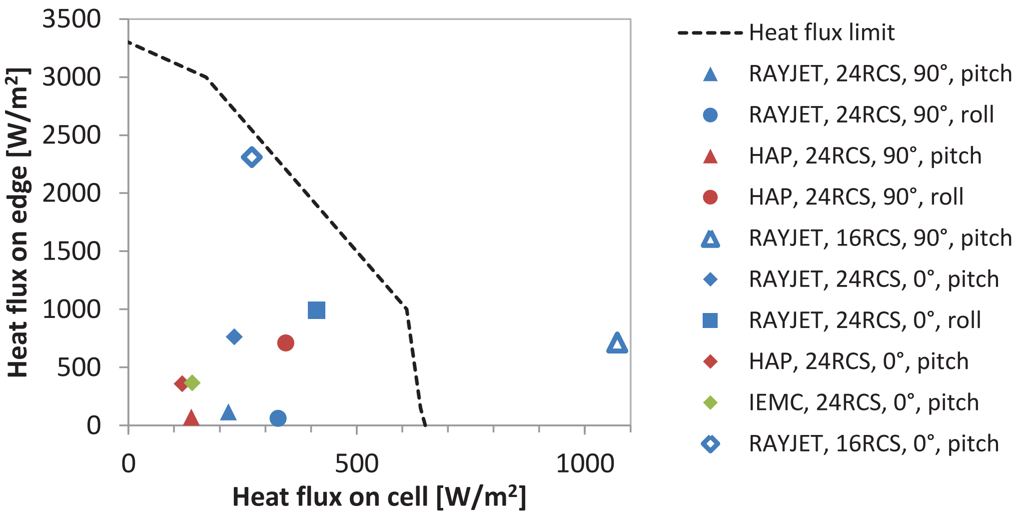
16 engine config. scenarios exceed allowable heat fluxes

All 24 engine config. scenarios acceptable

RCS plumes during roll control scenarios acceptable with 24 engine configuration, but not 16 engine configuration

RCS 4) ΔV burns

- For roll control during OMS-E or auxiliary burns
  - Longest burn durations
    - » Allowable heat fluxes are now < 3.5 kW/m^2
  - Again, 24 engine config found to be acceptable, but 16 engine config exceeds heat flux limit



RCS plumes during ΔV scenarios acceptable with 24 engine configuration, but not 16 engine configuration

Summary

- Plume impingement analysis performed for ESM
  - Significant changes from prior Orion SM design
- RCS plume heat fluxes drove design to close on 24 engine configuration
  - 16 engine configuration untenable with 4 solar arrays
  - Changes made to array design and allowable burn durations
- Notable plume interaction found when auxiliary engines fire simultaneously with main engine during ascent abort
  - Increased heat flux to ESM aft end

Ongoing work

- Complete OMS-E and auxiliary plume analyses still underway
- Other RCS plume impacts (e.g. contamination, force loading, etc.) found to be within acceptable limits
- Plume heating analysis on radiators and other surfaces ongoing

NASA